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DISPOSAL OF RADIOACTIVE IODINE IN SPACE

INTRODUCTION

Recent efforts at the Marshall Space Flight Center (MSFC) and elsewhere [1,2,3,4] have investigated the removal of radioactive waste from the Earth via transportation to some extraterrestrial location. These studies were primarily concerned with the elimination of high-level waste calcine from the tail-end of the fuel cycle.

Besides calcine, however, other waste products are of importance. These products include cladding, ash from reprocessing and refabrication, iodine, krypton, etc. This report will extend previous efforts by considering the space elimination of iodine.

Iodine can be handled in a very different manner from the high-level calcine wastes because it has very weak radiation (primarily beta with extremely low energy gamma radiation) and produces essentially no heat. Of the 14 possible iodine isotopes listed in ORIGEN output (A = 127, 128, 129, 130M, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139) [5], after 10 years only two remain, ${}_{53}I^{127}$ and ${}_{53}I^{129}$. The former is stable and the latter has a half-life of 17 million years. It is because of this extremely long half-life that virtually no heat is produced by radioactive decay.

The difficulty with iodine results from the fact that it is concentrated in biological chains and, due to the extremely long life and chemical properties, is a very poor candidate for terrestrial disposal. This same long life also makes nominal storage sites (such as the 0.86 AU orbit) less desirable.

Iodine occurs only in small quantities and constitutes only approximately 0.8 percent of the fission products.

THE CHEMICAL FORM OF IODINE TO BE CARRIED TO SPACE

Iodine is normally recovered from waste reprocessing by the Iodox Method, but other competing schemes have been identified [6]. The specific details of these processes are not of interest here; consequently, it suffices

to say that the end product of the chemistry has been directed toward the production of barium iodate, $Ba(IO_3)_2$. This material was chosen because it is easily synthesized and because it has a low leach rate in geologic storage.

The payoff parameters for space disposal are different from those for geologic storage. Low leach rates are desirable because of the possibility (extremely remote) of a spill; however, equally important is the fact that space disposal places a high premium upon the iodine that can be carried per unit volume of payload.

For this reason, various iodine compounds other than $Ba(IO_3)_2$ were considered. The iodine compounds considered were obtained from standard tables [7], and those that survived the initial winnowing are listed in Table 1. From Table 1 it can be seen that much work would have to be done before a final choice of compound is made. For example, the "i" label (for "insoluble") is wrong because nothing is truly insoluble for purposes of this mission. Nonetheless, there appear to be several candidate compounds for space disposal of iodine. In order of the payoff parameter of grams iodine per cc of compound they are BiI_3, PdI_2, MoI_2, WI_4, CuI, TlI, and $Ba(IO_3)_2$. The standard form, $Ba(IO_3)_2$, is thus the least desirable for space elimination. PdI_2 can be eliminated because it is too expensive and MoI_2 can be eliminated because it is not a fully verified compound. Thus, five options are left; however, more candidates could be expected with further investigation.

TABLE 1. SELECTED IODINE COMPOUNDS CONSIDERED FOR STUDY

Compound	Mass Density	Solubility in H_2O (gm/100 cc)	Grams I/cc	Comments
SbSI	?	i	?	
$Ba(IO_3)_2$	4.998	0.008	2.60	Standard form
$Bi(IO_3)_3$	?	i	?	
BiI_3	5.778	i	4.49	
CuI	5.62	0.0008	3.75	
MoI_2	5.278	i	3.83	Questionable existence
PdI_2	6.003	i	4.23	Expensive
TlI	7.098	i	2.72	
WI_4	5.2	i	3.82	Somewhat expensive

DESTINATION AND TRAJECTORY COMPUTATION

Two destinations for iodine payloads have been studied. The first is solar system escape, a destination which mathematically precludes return to man's environment and requires a large expenditure of energy. The second possible destination is a solar orbit at 0.86 AU. In this case, the payload is considerably larger but long-term stability is more questionable. It should be noted that the "rule of thumb" for disposing of wastes would require orbital stability for 170 million years. Studies which have been performed on the 0.86 AU orbit destination indicate stability for approximately 1 million years. The question of long-term stability has not been investigated, but for purposes of this study it will be assumed. (The prediction of orbital stability for 170 million years would be very difficult, if not impossible.)

The combination of vehicles which could best be utilized to attain each of the disposal conditions was investigated. It was concluded that the initial "to-orbit" phase could be accomplished by the Space Shuttle [1]. The terminal conditions for the Shuttle ascent were assumed to be a 160 n. mi. orbit and a payload of 29 492 kg.

Upper stage vehicles used in the study were a liquid oxygen/liquid hydrogen OTV and a solid stage, the inertial upper stage (IUS). In one case, a solid stage known as the "spinner" was utilized.

The OTV is characterized by a high specific impulse (470 s), a flowrate of 19.302 kg/s, and a thrust level of 88 964.4 N. Although the propulsion system remained unchanged, the vehicle sizing changed according to the particular mission profile. If the entire mission was accomplished with only one Shuttle, a burnout weight of 2800 kg was assumed, whereas a dual Shuttle launch assumed a burnout weight of 3096 kg.

The IUS is a lower performance vehicle having a specific impulse of 289.0 s, a flowrate of 4.106 kg/s, and a thrust level of 11 636.5 N. The burnout weight of the stage was calculated by assuming that 90 percent of the stage weight was propellant for the solar system escape missions. For the missions to 0.86 AU, the kick stage was only 76 percent fuel due to storage requirements for a mission extending over several months.

The disposal of iodine to the 0.86 AU orbit was investigated first. The investigation revealed that the 0.86 AU orbit mission may be flown in a variety of ways. Detailed data are presented for six cases (modes) and a graphical

summary of additional cases which achieve inclinations of more than 5 deg. The first two cases involve the use of two Shuttles. Shuttle No. 1 ascends to orbit and deploys the OTV vehicle. Once the OTV checkout is complete, Shuttle No. 2 ascends to rendezvous with the OTV and delivers the iodine waste package (to be described later) and the IUS vehicle. The waste package and IUS are then coupled with the OTV. The OTV burns out of low Earth orbit, separates from the IUS-waste package combination, and the waste package follows a Keplerian trajectory (Hohmann transfer) until the IUS ignites to place the waste package into the 0.86 AU orbit. The OTV utilizes its remaining propellant to return to low Earth orbit where it is recovered by Shuttle No. 1 and returned to Earth. Mode 1 assumes that the final orbit at 0.86 AU is in the plane of the ecliptic, whereas Mode 2 assumes that the final trajectory is inclined at 5 deg to the ecliptic.[1]

Modes 3 and 4 vary the inclination at 0 and 5 deg, respectively, but assume only one Shuttle launch each. That is, a single Shuttle is required to carry the OTV, IUS, and waste package.

Modes 5 and 6 utilize one and two Shuttles, respectively. The OTV is used for every burn, i.e., the IUS is replaced by an OTV burn. The OTV is expendable in this case.

Table 2 lists the payloads predicted for Modes 1 through 4. It should be noted that the two-Shuttle launch is less efficient than the one-Shuttle launch with respect to payload delivered per launch. Figure 1 shows the burn profile for Modes 1 through 4. Tables 3 through 8 present the detailed burn history for each of the 6 modes.

TABLE 2. PREDICTED PAYLOADS FOR MODES 1, 2, 3, AND 4

Mode	Burns	OTV Burns/ OTV Usage	IUS Burns	Mass to 0.86 AU (kg)	Inclination (deg)
1	5	4/Reuse	1	7 884	0
2	5	4/Reuse	1	7 230	5
3	5	4/Reuse	1	4 207	0
4	5	4/Reuse	1	3 430	5
5	3	3/Expend	0	7 367	0
6	3	3/Expend	0	11 638	0

1. Inclined orbits at 0.86 AU are more stable than are orbits in the plane of the ecliptic [4].

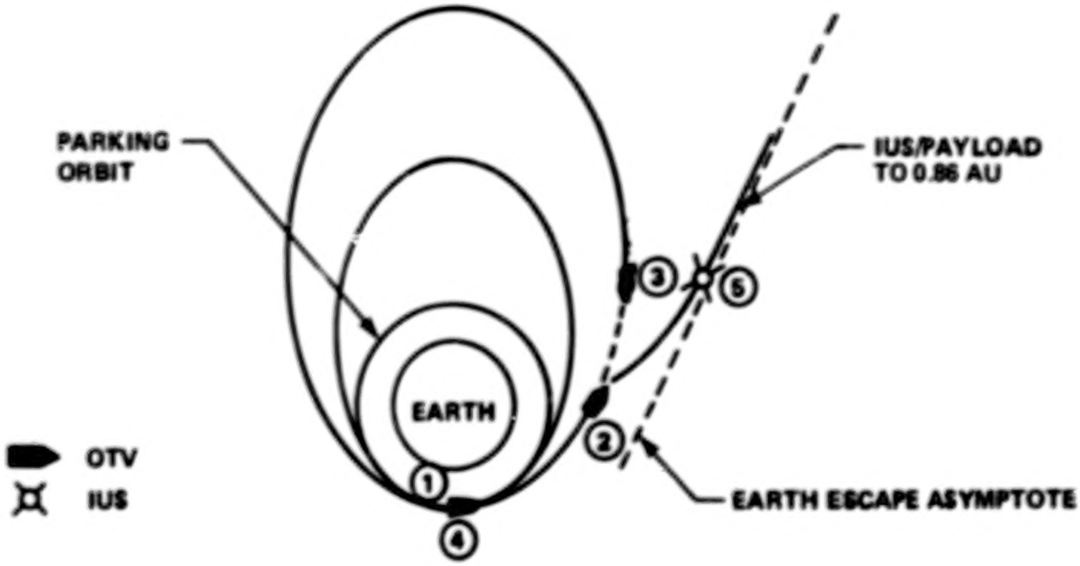

Figure 1. Burn profile for Modes 1 through 4 (0.86 AU solar orbit employing a reusable OTV).

TABLE 3. DETAILED BURN HISTORY FOR 0.86 AU ORBIT, MODE 1 (TWO-SHUTTLE LAUNCH, 0 deg INCLINATION, 7884 kg PAYLOAD)

Burn No.	Stage	M_O (kg)	M_F (kg)	Burn Time (s)	Propellant (kg)
1	OTV	43 060.9	29 752.2	689.5	13 308.7
2	OTV	29 752.2	21 071.4	449.7	8 680.8
3	OTV	6 346.6	5 563.2	40.6	983.4
4	OTV	5 563.2	3 096.0	127.8	2 467.2
5	IUS[a]	14 724.9	9 841.6	1189.3	4 883.3

a. IUS Burnout Mass = 1542 kg.

TABLE 4. DETAILED BURN HISTORY FOR 0.86 AU ORBIT, MODE 2 (TWO-SHUTTLE LAUNCH, 0 deg INCLINATION, 7230 kg PAYLOAD)

Burn No.	Stage	M_O (kg)	M_F (kg)	Burn Time (s)	Propellant (kg)
1	OTV	41 839.1	30 644.2	580.0	11 194.9
2	OTV	30 644.2	20 003.6	551.3	10 640.6
3	OTV	6 500.5	5 705.6	41.2	794.9
4	OTV	5 705.6	3 096.0	135.2	2 609.6
5	IUS[a]	13 503.1	9 025.0	1090.7	4 478.1

a. IUS Burnout Mass = 1414.14 kg.

TABLE 5. DETAILED BURN HISTORY FOR 0.86 AU ORBIT, MODE 3 (ONE-SHUTTLE LAUNCH, 0 deg INCLINATION, 4207 kg PAYLOAD)

Burn No.	Stage	M_O (kg)	M_F (kg)	Burn Time (s)	Propellant (kg)
1	OTV	28 283.0	18 484.3	507.7	9798.7
2	OTV	18 484.3	13 879.8	238.6	4604.5
3	OTV	6 022.2	5 274.4	38.7	747.8
4	OTV	5 274.4	2 950.0	120.4	2324.4
5	IUS[a]	7 857.5	5 251.7	636.6	2605.8

a. IUS Burnout Mass = 823 kg.

TABLE 6. DETAILED BURN HISTORY FOR 0.86 AU ORBIT, MODE 4 (ONE-SHUTTLE LAUNCH, 5 deg INCLINATION, 3430 kg PAYLOAD)

Burn No.	Stage	M_O (kg)	M_F (kg)	Burn Time (s)	Propellant (kg)
1	OTV	28 283	17 665.3	550.1	10 617.7
2	OTV	17 665.3	13 000.9	241.6	4 664.4
3	OTV	6 437.8	5 238.4	62.1	1 199.4
4	OTV	5 238.4	2 950.0	118.5	2 288.4
5	IUS[a]	6 563.1	4 319.1	546.5	2 244.0

a. IUS Burnout Mass = 708.6 kg.

TABLE 7. DETAILED BURN HISTORY FOR 0.86 AU ORBIT, MODE 5 (ONE-SHUTTLE LAUNCH, 0 deg INCLINATION, 10 704 kg PAYLOAD)

Burn No.	Stage	M_O (kg)	M_F (kg)	Burn Time (s)	Propellant (kg)
1	OTV	28 283.0	20 379.1	409.5	7903.9
2	OTV	20 379.1	13 895.2	335.9	6483.9
3	OTV	13 845.2	10 704.4	162.7	3140.8

TABLE 8. DETAILED BURN HISTORY FOR 0.86 AU ORBIT, MODE 6 (TWO-SHUTTLE LAUNCH, 0 deg INCLINATION, 15 346.2 kg PAYLOAD)

Burn No.	Stage	M_O (kg)	M_F (kg)	Burn Time (s)	Propellant (kg)
1	OTV	40 634.0	29 407.3	581.6	11 226.7
2	OTV	29 407.3	19 898.9	492.6	9 508.4
3	OTV	19 848.9	15 346.2	233.3	4 502.7

Although the previously mentioned work assumed that the 0.86 AU orbit was stable, work presented in Reference 4 indicates that the stability of the 0.86 AU orbit increases as the inclination increases. For this reason, other cases were studied that increased the inclination of the orbit until all payload vanished (Fig. 2). In Figure 2 it was assumed that a single Shuttle was employed and that the OTV used in the mission had to be recovered for reuse. In this case, the payload is expected to vanish at an inclination to the ecliptic of 12.8 deg.

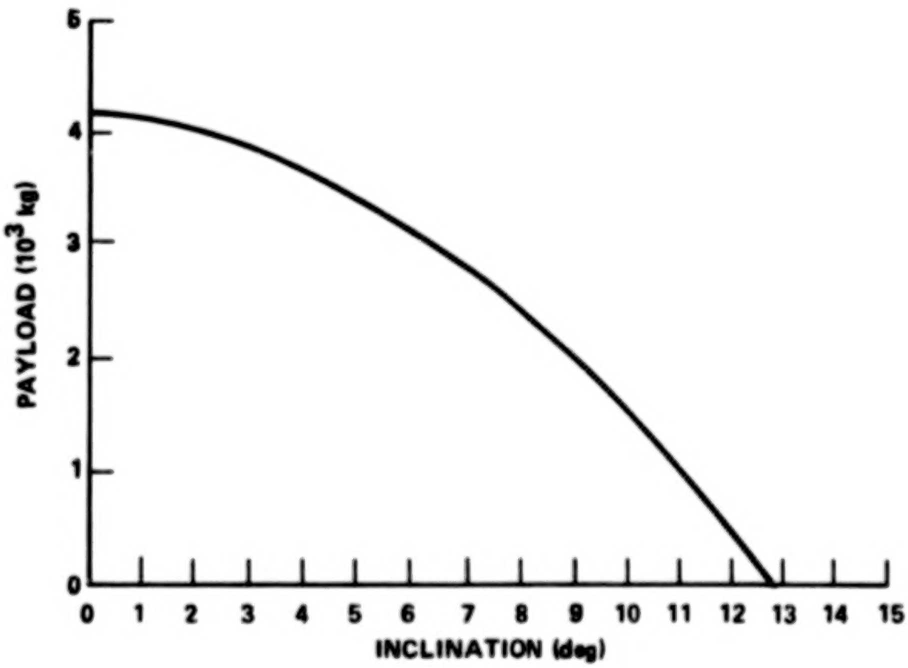

Figure 2. Inclination versus payload trade study (one-Shuttle launch to 0.86 AU solar orbit employing a reusable OTV).

In an alternative mode, the OTV is expended rather than returned for reuse. This is a more efficient approach (from the propulsive standpoint) than is the necessity to return for reuse procedure. From Figure 3 it is noted that in the expendable mode the OTV can deliver a payload of 3850 kg at 12.8 deg and can deliver a payload of 1450 kg even at a 20 deg inclination.

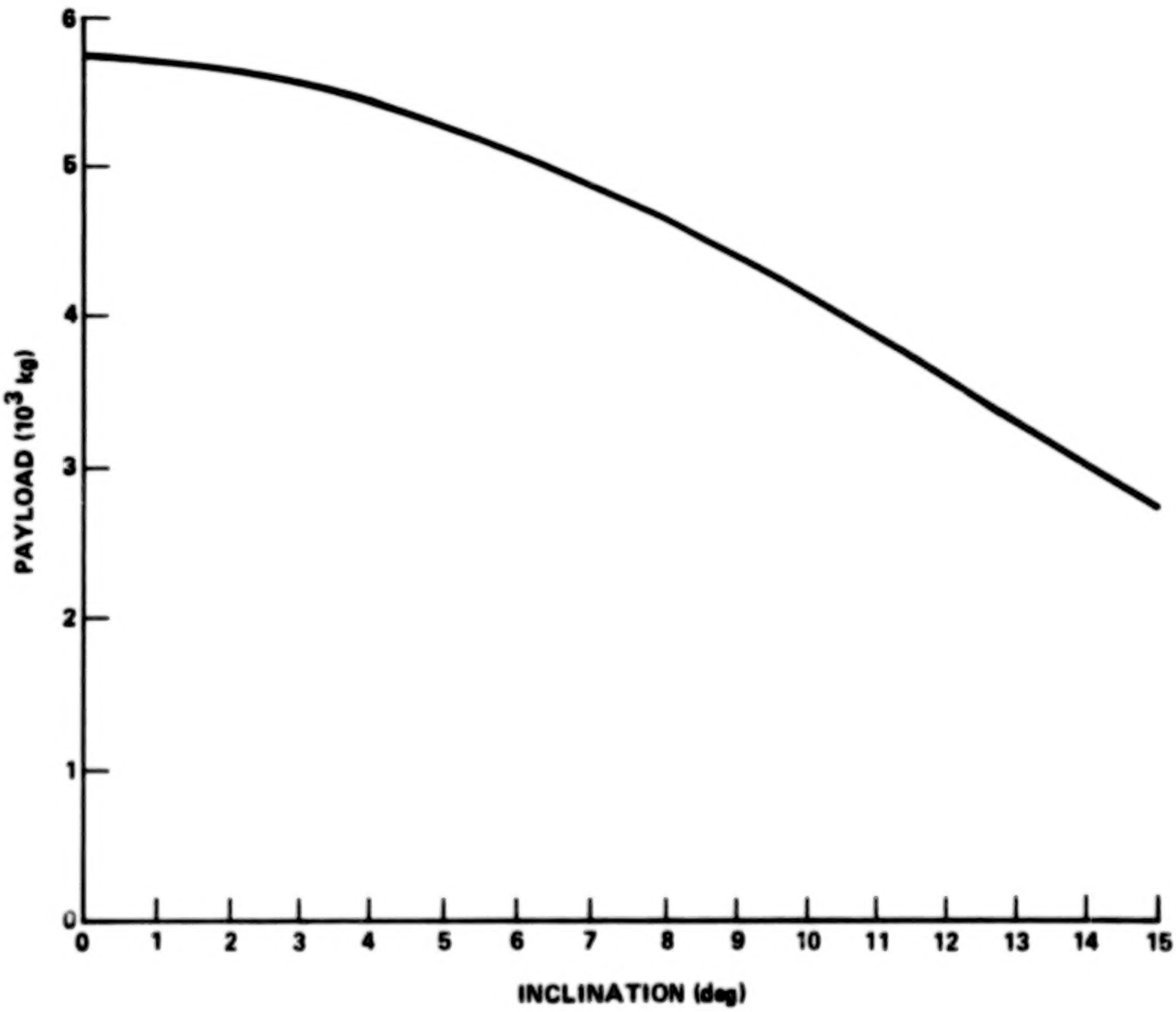

Figure 3. Inclination versus payload trade study (one-Shuttle launch to 0.86 AU solar orbit employing an expendable OTV).

In the case of solar system escape, there are also six modes to be considered. Mode 1 assumes that two Shuttles are employed and that the OTV is utilized to produce two "perigee burns." Mode 2 is similar to Mode 1 but utilizes only one "perigee burn." Mode 3 again employs two Shuttles but restricts the OTV to reusability, i.e., it must retain sufficient fuel to return to the Shuttle orbit for pickup and reuse. Mode 4 employs the use of only one Shuttle and assumes an expendable OTV. Mode 5 completes the option combinations by assuming one Shuttle launch and a reusable OTV.

Mode 6 is a drastic departure from the previously discussed combinations. This mode employs a combination of two IUS stages and a small solid stage dubbed a "spinner." (Spinner specific impulse is the same as the main IUS stage.) This case is carried as a reference, but it produces such a low payload it is not detailed.

Table 9 lists the expected payload from each mode. Figures 4 and 5 show the burn profile for solar escape missions with a reusable and expendable OTV, respectively. Tables 10 through 14 list the detailed burn history of each mode.

TABLE 9. EXPECTED PAYLOADS FOR SOLAR ESCAPE MISSIONS

Mode	Burns	OTV Burns/ OTV Usage	IUS Burns	Escape Mass (kg)
1	3	2/ Expend	1	1740
2	2	1/ Expend	1	1462
3	5	4/ Reuse	1	719
4	3	2/ Expend	1	1154
5	5	4/ Reuse	1	452
6	2	No OTV	2 + Spinner	379

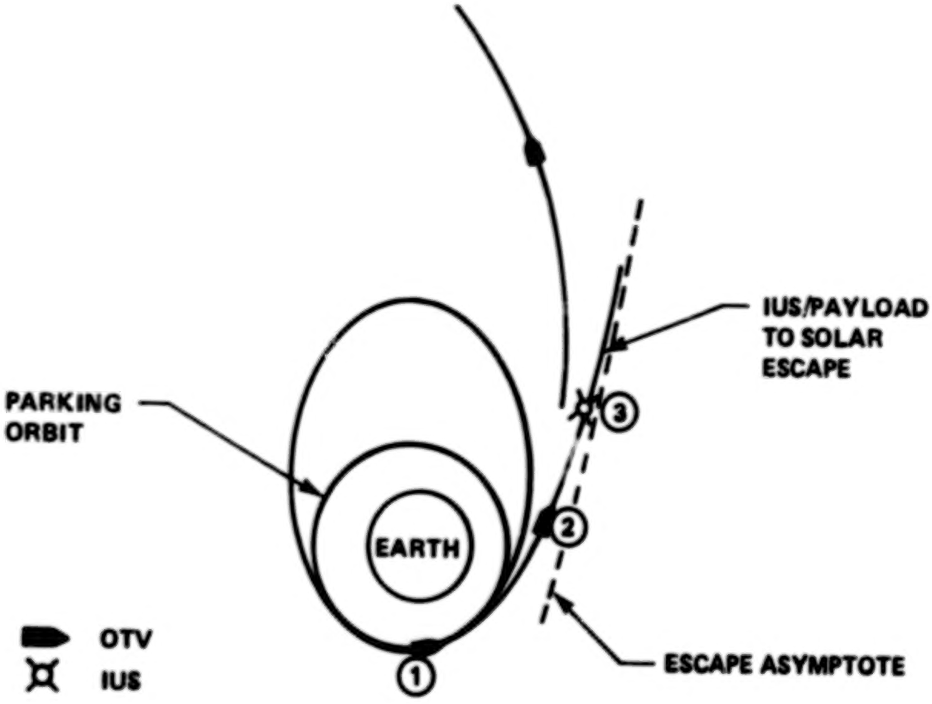

Figure 4. Solar escape profile employing an expendable OTV.

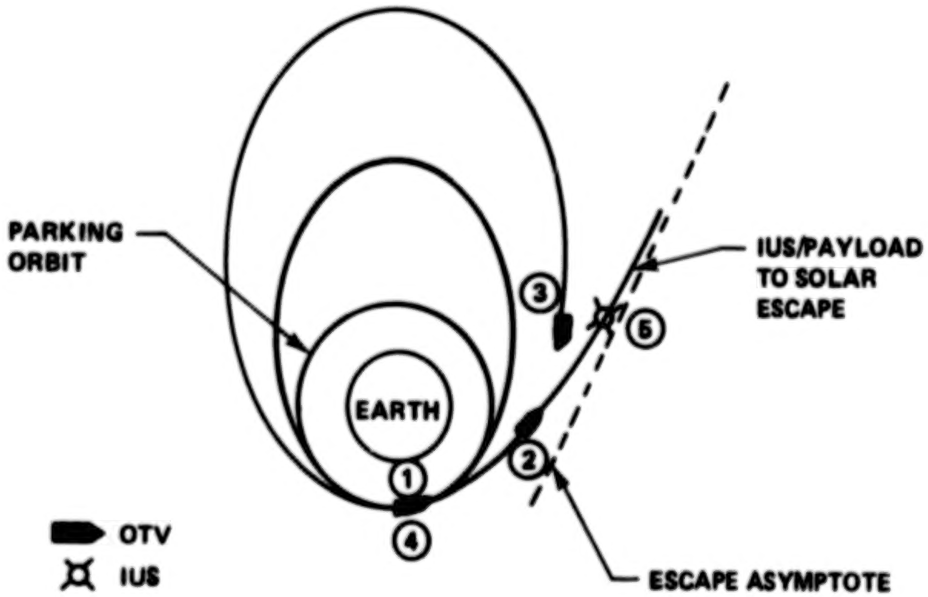

Figure 5. Solar escape profile employing a reusable OTV.

TABLE 10. DETAILED BURN HISTORY FOR SOLAR SYSTEM ESCAPE, MODE 1 (TWO-SHUTTLE LAUNCH, EXPENDABLE OTV, 1740 kg PAYLOAD)

Burn No.	Stage	M_O (kg)	M_F (kg)	Burn Time (s)	Propellant (kg)
1	OTV	34 140.4	18 365.6	1089.7	15 774.8
2	OTV	18 365.6	8 900.4	653.8	9 465.2
3	IUS[a]	5 629.4	2 129.3	53.7	3 500.0

a. IUS Burnout Mass = 389 kg.

TABLE 11. DETAILED BURN HISTORY FOR SOLAR SYSTEM ESCAPE, MODE 2 (TWO-SHUTTLE LAUNCH, EXPENDABLE OTV, 1462 kg PAYLOAD)

Burn No.	Stage	M_O (kg)	M_F (kg)	Burn Time (s)	Propellant (kg)
1	OTV	32 131.6	6891.6	1307.6	25 240
2	IUS[a]	3 684.5	1684.6	30.7	2 000

a. IUS Burnout Mass = 222 kg.

TABLE 12. DETAILED BURN HISTORY FOR SOLAR SYSTEM ESCAPE, MODE 3 (TWO-SHUTTLE LAUNCH, REUSABLE OTV, 719 kg PAYLOAD)

Burn No.	Stage	M_O (kg)	M_F (kg)	Burn Time (s)	Propellant (kg)
1	OTV	38 769.9	24 077.1	761.2	14 692.8
2	OTV	24 077.1	17 360.0	348.0	6 717.1
3	OTV	6 926.3	5 491.5	74.3	1 734.8
4	OTV	5 491.5	3 096.0	124.1	2 395.4
5	IUS[a]	10 433.7	1 724.4	133.7	8 709.3

a. IUS Burnout Mass = 968 kg.

TABLE 13. DETAILED BURN HISTORY FOR SOLAR SYSTEM ESCAPE, MODE 4 (ONE-SHUTTLE LAUNCH, EXPENDABLE OTV, 1154 kg PAYLOAD)

Burn No.	Stage	M_O (kg)	M_F (kg)	Burn Time (s)	Propellant (kg)
1	OTV	28 484	17 831.7	551.9	10 652.3
2	OTV	17 831.7	8 554.7	480.6	9 277.0
3	IUS[a]	5 604.7	1 559.2	61.5	4 005.5

a. IUS Burnout Mass = 445 kg.

TABLE 14. DETAILED BURN HISTORY FOR SOLAR SYSTEM ESCAPE, MODE 5 (ONE-SHUTTLE LAUNCH, REUSABLE OTV, 452 kg PAYLOAD)

Burn No.	Stage	M_O (kg)	M_F (kg)	Burn Time (s)	Propellant (kg)
1	OTV	28 484.0	17 051.0	592.3	11 433.0
2	OTV	17 051.0	12 056.0	258.8	4 995.0
3	OTV	6 978.0	5 170.2	93.7	1 807.8
4	OTV	5 170.2	2 950.0	115.0	2 220.2
5	IUS[a]	5 078.0	936.0	63.6	4 142.0

a. IUS Burnout Mass = 460 kg.

Each of the previously mentioned trajectories was calculated on a quasi-optimization deck named SAMBO [8]. In each case the weight staging ratio between the OTV and IUS was optimized to produce maximum final mass. The burn history was similarly optimized.

QUANTITY OF IODINE GENERATED

Although the quantity of iodine generated per metric ton of uranium charged to the reactor was mentioned previously, we have yet to describe the total production curve of iodine as a function of years from the present time. Table 15 lists iodine generated as a function of year. The assumed nuclear power generating capacity is taken from Reference 9. In addition to the generated iodine, Table 15 gives the accumulated mass of to-be-transported wastes as BiI_3, WI_4, CuI, $Ba(IO_3)_2$, and TlI.

It is interesting to note that although the iodine generated by the present nuclear power industry is small, the cumulative totals by the year 2005 amount to a substantial mass. Additionally, when the iodine is incorporated into a

TABLE 15. CUMULATIVE IODINE MASS AS ELEMENT AND COMPOUNDS

Year	Iodine Generated (kg)	Cumulative Iodine (kg)	Mass as BiI_3 (kg)	Mass as WI_4 (kg)	Mass as CuI (kg)	Mass as $Ba(IO_3)_2$ (kg)	Mass as TlI (kg)
Pre-1975	370	370	473	504	555	710	966
1975	139	509	651	693	764	977	1 329
1976	168	677	865	922	1 016	1 299	1 767
1977	205	882	1 127	1 201	1 324	1 693	2 302
1978	243	1 125	1 438	1 532	1 688	2 159	2 937
1979	277	1 402	1 792	1 910	2 104	2 691	3 660
1980	304	1 706	2 181	2 324	2 560	3 274	4 453
1981	330	2 036	2 603	2 773	3 055	3 908	5 315
1982	357	2 393	3 059	3 260	3 591	4 593	6 246
1983	399	2 792	3 569	3 803	4 190	5 359	7 288
1984	457	3 249	4 153	4 426	4 875	6 236	8 481
1985	525	3 774	4 824	5 141	5 663	7 244	9 851
1986	611	4 385	5 605	5 973	6 580	8 417	11 446
1987	692	5 077	6 490	6 916	7 619	9 745	13 252
1988	761	5 838	7 463	7 953	8 761	11 205	15 329

TABLE 15. (Continued)

Year	Iodine Generated (kg)	Cumulative Iodine (kg)	Mass as BiI_3 (kg)	Mass as WI_4 (kg)	Mass as CuI (kg)	Mass as $Ba(IO_3)_2$ (kg)	Mass as TlI (kg)
1989	826	6 664	8 518	9 078	10 000	12 791	17 395
1990	890	7 554	9 656	10 290	11 336	14 499	19 718
1991	961	8 515	10 885	11 599	12 778	16 344	22 227
1992	1036	9 551	12 209	13 010	14 332	18 332	24 931
1993	1114	10 665	13 633	14 528	16 004	20 470	27 839
1994	1194	11 859	15 159	16 154	17 796	22 762	30 955
1995	1279	13 138	16 794	17 897	19 715	25 217	34 294
1996	1371	14 509	18 547	19 764	21 772	27 848	37 873
1997	1456	15 965	20 408	21 748	23 957	30 643	41 673
1998	1558	17 523	22 399	23 870	26 295	33 633	45 740
1999	1650	19 173	24 509	26 118	28 771	36 800	50 047
2000	1740	20 913	26 733	28 488	31 382	40 140	54 589
2001	1823	22 736	29 063	30 971	34 118	43 639	59 347
2002	1883	24 619	31 470	33 536	36 943	47 253	64 263
2003	1933	26 552	33 941	36 169	39 844	50 964	69 308

TABLE 15. (Concluded)

Year	Iodine Generated (kg)	Cumulative Iodine (kg)	Mass as BiI_3 (kg)	Mass as WI_4 (kg)	Mass as CuI (kg)	Mass as $Ba(IO_3)_2$ (kg)	Mass as TlI (kg)
2004	1997	28 549	36 494	38 890	42 841	54 797	74 521
2005	2012	30 561	39 066	41 631	45 860	58 658	79 773

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compound, the mass increases considerably. It should be noted that if Tl rather than Bi was chosen as a compounding agent, the mass of weight to be carried more than doubles.[2]

When considering the small payloads per flight discussed earlier, it is obvious that the chemical form of the iodine waste is of critical importance.

IODINE CONTAINER DESIGN

Once the chemical form of the iodine has been defined, the important question of package design must be addressed. The package must fulfill the conditions of the following functions:

1) It must physically hold the iodine compound without corrosive interactions.

2) It must shield the iodine radiation.

3) It must protect the iodine from release to the environment under a credible accident scenario that could befall the transportation system. This implies reentry containment from both thermal and impact loads.

Condition 1 is easily met because most candidate compounds are usually benign with respect to corrosion of most structural steels. (This assumption will be investigated in detail if work continues on the elimination of iodine in space.) Condition 2 is also easily met since radiation from I^{129} is considered trivial and can be shielded by virtually any containment. As mentioned earlier, the thermal output of iodine is so low ($\sim 1.7 \times 10^{-10}$ W/gm) that problems from internal heating are totally negligible.

Condition 3 presents the most difficult packaging consideration. Substantial mechanical and thermal protection are required if the iodine waste package is to be rendered fail-safe with respect to maximum credible accident scenarios. The package design was modeled from information contained in Reference 2, but with appropriate modifications. Two basic configurations were investigated. The first configuration assumed that the wastes were packed into a hemispherical container with a containment shield over the dome and the flat rear portion of the hemisphere. A conical drag collar was fixed at the back

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2. It is apparent that light-element iodides may prove useful to the disposal scheme. In general, however, they are water soluble and have low mass densities.

rim of the hemisphere to act as an aerodynamic brake if the package had to be aborted from a failed Shuttle. The entire package was assumed to be covered by minimum heat transfer insulation and a reentry ablator.

The specific design considerations that were employed in the design of the containment shell assumed that a solid steel container was used. The thickness of the shell was constrained to 5 cm maximum. This constraint was believed to be a reasonable compromise between higher-than-orbital reentry velocities (requiring a heavier shell) and a possible lightening of the shell via honeycomb structure.

The required thickness of the shell cap was calculated by the Humphreys and Bodner theory or set at 5 cm, whichever was less. The cap (0 to 45 deg) was held at a constant thickness. The required shell thickness at 90 deg was again calculated from Humphreys and Bodner, and a linear variation of thickness was assumed between 45 and 90 deg. The back cap of the hemisphere was assumed to be the same thickness as at the 90 deg point. The flare configuration was sized to give a constant ballistic coefficient (as a function of payload and cocoon mass), and this flare was assumed to be fabricated of steel which was one-third the thickness of the shell at the 90 deg point.

The reentry protection was provided by a layer of minimum conductivity material (Min-K) which covered the front of the configuration and a layer of ablative material was assumed to overlay the insulation. The Min-K insulation was assumed to have a density of 1 gm/cc and a thickness of 1.27 cm. The ablator was assumed to be of density 2.25 gm/cm^3 and of thickness 1.91 cm. Neither material was scaled in thickness as the payload varied.

Another alternative configuration for the waste package is a simple sphere. The iodine was presumed to be contained within a steel shell that was again constrained to a thickness of 5 cm or to the thickness predicted by Humphreys and Bodner, whichever was less. Thermal insulation and an ablator were added as for the flared case. The fact that the spherical configuration would reenter at a higher velocity than would the flared configuration (thus requiring a thicker containment shell) was ignored.

Figures 6 and 7 show the reentry configurations for the spherical and flared cases, respectively.

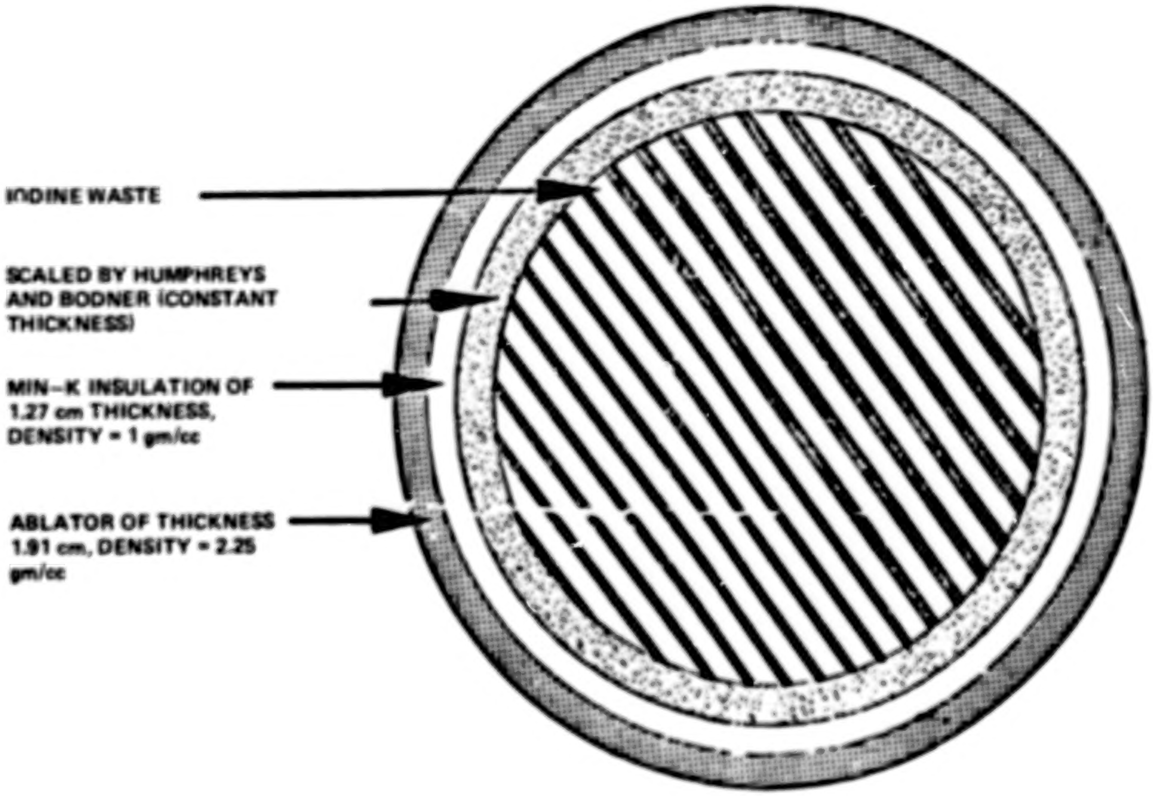

Figure 6. Spherical reentry configuration for iodine waste package.

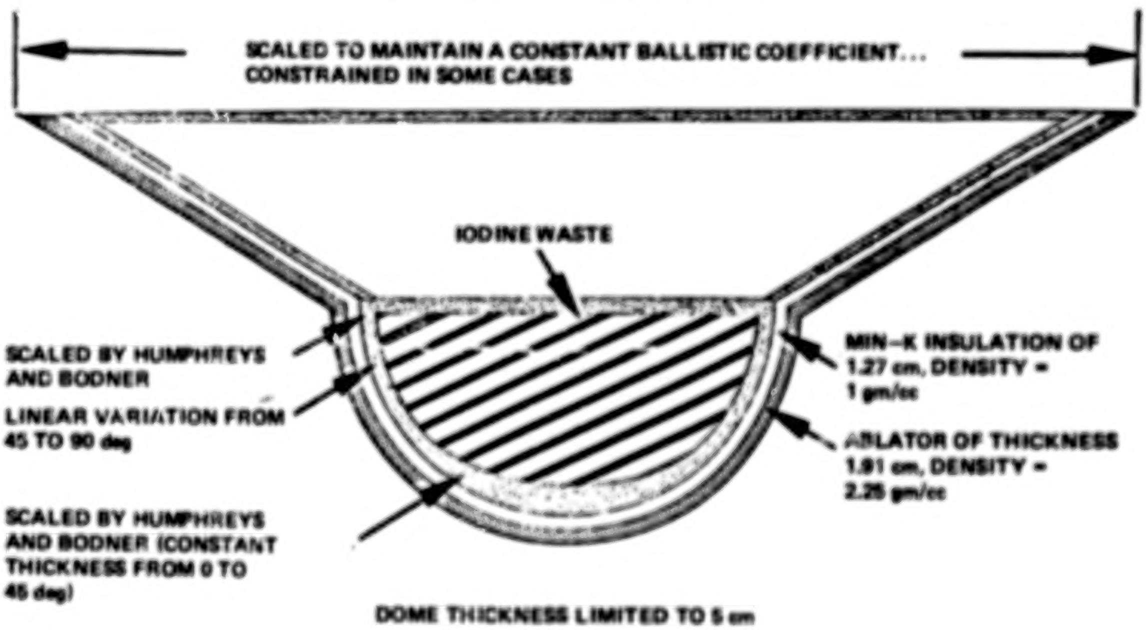

Figure 7. Flared reentry configuration for iodine waste package.

PAYLOADS AND TRAFFIC DENSITY

The actual number of Shuttle flights which would be necessary to transport the iodine generated at commercial nuclear power plants from man's environment have not been determined. However, the total mass which can be delivered to each destination (using various vehicle combinations) and the projected rate of iodine generation for each of five different iodine compounds (Table 15) has been calculated. The most important unknown still remaining is the density of the waste to be carried. This problem cannot be solved by simply "looking up" the density of, for example, bismuth triiodide because such densities are usually theoretical and cannot be achieved in practice.

There are several variables which must be considered when predicting payloads for each combination of parameters. First is the destination, either 0.86 AU or solar system escape. Besides the destination, the mode (one or two Shuttles, number of burns, expendable or reusable OTV, etc.) and the packaging design (flared or spherical configuration) must be considered. Finally, variations in density must be considered. The results of this combination of conditions are given in Table 16 for the 0.86 AU destination and in Table 17 for the two-Shuttle mission to solar system escape. Table 18 gives the same data for the one-Shuttle mission to solar system escape.

The flight density is still required. To reduce the number of cases to a reasonable number, flight densities were calculated only for a waste density of 4 gm/cc. Table 19 gives the results for five compounds for a 0.86 AU destination, a reusable OTV, and a flared hemispherical waste package configuration. Table 20 gives similar results but assumes a spherical waste package configuration.

Tables 21 through 24 give flight densities for solar system escape missions. Tables 21 and 22 give data for the expended OTV (Mode 1) and Tables 23 and 24 give data for the reusable OTV (Mode 3), with variations occurring due to the use of a hemispherical or spherical container. Traffic densities for Modes 2, 4, 5, and 6 have not been calculated.

TABLE 16. WASTE MASS PARAMETERIZATION FOR THE 0.86 AU SOLAR ORBIT MISSION

Waste Density (gm/cc)	Mode No. 1 Sphere (kg)	Mode No. 1 Hemi w/ Flare (kg)	Mode No. 2 Sphere (kg)	Mode No. 2 Hemi w/ Flare (kg)	Mode No. 3 Sphere (kg)	Mode No. 3 Hemi w/ Flare (kg)	Mode No. 4 Sphere (kg)	Mode No. 4 Hemi w/ Flare (kg)
2.5	4268	3772	3859	3409	2043	1788	1603	1392
3.0	4553	4000	4121	3619	2200	1913	1732	1494
3.5	4786	4184	4337	3789	2331	2015	1839	1578
4.0	4981	4338	4518	3931	2441	2101	1931	1649
4.5	5148	4468	4672	4051	2537	2175	2010	1710
5.0	5292	4579	4806	4155	2620	2239	2079	1763

TABLE 17. WASTE MASS PARAMETERIZATION FOR THE SOLAR SYSTEM ESCAPE MISSION (TWO-SHUTTLE LAUNCH)

Waste Density (gm/cc)	Mode No.					
	1		2		3	
	Sphere (kg)	Hemi w/ Flare (kg)	Sphere (kg)	Hemi w/ Flare (kg)	Sphere (kg)	Hemi w/ Flare (kg)
2.5	707.0	586.0	571.4	464.5	236.1	167.4
3.0	772.5	636.5	626.0	506.3	261.7	185.7
3.5	827.5	678.6	672.5	541.7	284.0	200.3
4.0	876.5	715.0	713.0	571.3	303.3	214.0
4.5	917.8	746.4	748.0	598.0	321.0	226.0
5.0	954.3	774.5	779.2	621.0	336.4	236.5

TABLE 18. WASTE MASS PARAMETERIZATION FOR THE SOLAR SYSTEM ESCAPE MISSION (ONE-SHUTTLE LAUNCH)

Waste Density (gm/cc)	Mode No.			
	4		5	
	Sphere (kg)	Hemi w/ Flare (kg)	Sphere (kg)	Hemi w/ Flare (kg)
2.5	427.0	335.7	130.5	77.5
3.0	469.5	367.0	145.8	86.7
3.5	506.0	394.1	159.4	94.8
4.0	538.0	417.7	171.3	102.0
4.5	566.0	438.0	182.0	108.4
5.0	590.7	456.2	191.6	114.2

TABLE 19. FLIGHT DENSITY RESULTS FOR IODINE COMPOUND ASSUMING A 0.86 AU DESTINATION, A REUSABLE OTV, AND A FLARED HEMISPHERICAL WASTE PACKAGE CONFIGURATION

Year	BiI_3	WI_4	CuI	$Ba(IO_3)_2$	TlI
1	2	2	2	3	3
2	0	0	0	0	1
3	0	0	1	1	1
4	1	1	0	0	1
5	0	0	1	1	1
6	1	1	0	1	1
7	0	1	1	1	1
8	1	0	1	0	1
9	0	1	0	1	2
10	1	1	1	1	1
11	1	0	1	2	2
12	1	1	1	1	1
13	1	1	1	1	2
14	0	1	1	1	2
15	1	1	1	2	2
16	1	1	2	1	2
17	2	1	1	2	2
18	1	2	1	2	2
19	1	1	2	2	3
20	1	1	1	1	2
Total	16	17	19	24	33

TABLE 20. FLIGHT DENSITY RESULTS FOR IODINE COMPOUNDS ASSUMING A 0.86 AU DESTINATION, A REUSABLE OTV, AND A SPHERICAL WASTE PACKAGE CONFIGURATION

Year	BiI_3	WI_4	CuI	$Ba(IO_3)_2$	TlI
1	1	1	2	2	3
2	1	1	0	1	1
3	0	0	0	0	0
4	0	0	1	1	1
5	1	1	0	0	1
6	0	0	1	1	1
7	1	1	0	1	1
8	0	0	1	0	1
9	1	1	0	1	1
10	0	1	1	1	1
11	1	0	1	1	1
12	0	1	1	1	2
13	1	1	1	1	1
14	1	1	0	1	2
15	1	0	1	2	2
16	1	1	1	1	1
17	1	1	2	1	2
18	1	1	1	2	2
19	1	1	1	1	2
20	1	2	1	2	2
Total	14	15	16	21	28

TABLE 21. FLIGHT DENSITY RESULTS FOR IODINE COMPOUNDS ASSUMING A SOLAR SYSTEM ESCAPE DESTINATION, AN EXPENDED OTV, AND A HEMISPHERICAL WASTE PACKAGE CONFIGURATION

Year	BiI_3	WI_4	CuI	$Ba(IO_3)_2$	TlI
1	3	3	3	3	4
2	3	3	3	4	5
3	3	3	4	4	6
4	3	3	4	4	6
5	3	3	4	5	6
6	3	3	4	5	6
7	3	4	4	5	7
8	3	4	4	5	7
9	4	4	4	6	7
10	4	4	4	6	8
11	4	4	4	6	9
12	4	4	5	6	9
13	4	5	5	7	9
14	4	5	5	7	10
15	5	5	6	7	10
16	5	5	5	8	11
17	6	6	7	8	10
18	5	6	6	8	12
19	6	6	7	9	12
20	6	6	7	9	12
Total	81	86	95	124	166

TABLE 22. FLIGHT DENSITY RESULTS FOR IODINE COMPOUNDS ASSUMING A SOLAR SYSTEM ESCAPE DESTINATION, AN EXPENDED OTV, AND A SPHERICAL WASTE PACKAGE CONFIGURATION

Year	BiI_3	WI_4	CuI	$Ba(IO_3)_2$	TlI
1	2	2	2	2	3
2	2	2	2	2	4
3	2	2	2	3	4
4	2	2	2	3	5
5	2	2	3	3	5
6	2	3	3	4	5
7	3	3	3	4	5
8	3	3	3	5	6
9	3	3	3	5	6
10	3	3	4	5	6
11	3	3	4	5	7
12	3	3	4	5	7
13	3	4	4	5	7
14	4	4	4	5	7
15	4	4	5	6	8
16	4	4	5	6	8
17	4	4	5	6	8
18	5	5	5	7	9
19	4	4	5	6	9
20	1	5	6	7	9
Total	63	65	74	94	128

TABLE 23. FLIGHT DENSITY RESULTS FOR IODINE COMPOUNDS ASSUMING A SOLAR SYSTEM ESCAPE DESTINATION, A REUSABLE OTV, AND A HEMISPHERICAL WASTE PACKAGE CONFIGURATION

Year	BiI_3	WI_4	CuI	$Ba(IO_3)_2$	TlI
1	3	3	3	3	3
2	8	8	8	8	8
3	12	12	12	12	12
4	14	14	14	16	16
5	14	14	16	20	20
6	14	14	18	22	27
7	15	14	19	24	29
8	15	15	20	26	30
9	16	15	20	26	33
10	16	15	20	26	35
11	17	16	21	26	36
12	17	18	21	28	39
13	18	20	21	28	41
14	19	24	21	30	43
15	20	24	23	31	46
16	21	25	24	32	48
17	22	25	26	33	51
18	23	26	27	36	52
19	24	26	28	36	55
20	24	26	28	36	55
Total	332	354	390	499	679

TABLE 24. FLIGHT DENSITY RESULTS FOR IODINE COMPOUNDS ASSUMING A SOLAR SYSTEM ESCAPE DESTINATION, A REUSABLE OTV, AND A SPHERICAL WASTE PACKAGE CONFIGURATION

Year	BiI_3	WI_4	CuI	$Ba(IO_3)_2$	TlI
1	3	3	3	3	3
2	4	4	4	4	8
3	6	6	8	8	12
4	8	8	8	12	12
5	8	8	8	12	14
6	8	9	12	12	16
7	8	9	12	12	18
8	9	10	12	12	20
9	9	10	12	14	22
10	9	12	12	16	22
11	10	12	12	16	24
12	11	12	12	16	24
13	11	12	12	16	24
14	12	12	13	18	24
15	13	12	13	18	24
16	13	13	15	20	25
17	13	14	15	20	27
18	14	15	16	22	28
19	14	15	16	22	28
20	15	15	17	24	30
Total	198	211	232	297	405

CONCLUSIONS

The foregoing study has been brief and should be regarded as a scoping exercise rather than a definitive document. Additional work is needed to:

1) Choose a specific destination and mode profile

2) Extend the study of necessary waste containers with respect to impulse loading

3) Determine an optimal waste compound

4) Decide upon many specific issues that are neglected in this study.

The destination which would ultimately be chosen if the space elimination of iodine is undertaken is particularly important. It should be noted that the "rule-of-thumb" stability requirement for iodine (170 million years) is far beyond the confidence of any celestial mechanics calculations. Thus, if, for example, solar orbit at 0.86 AU is to be chosen, then one certainly must assume that instability will occur. Indeed, the rational policy might be to construct a deliberately erodible container which would distribute the contents of the package in space on a time scale of a few hundred thousand years. This time scale would preclude accumulations at the Earth. The fate of the particles dispersed into open space would differ according to their size distribution and, thus, would require investigation.

While solar orbits yield large payloads, the solar system escape modes yield absolute isolation. The only objection to solar system escape seems to be the small payloads that would be delivered.

Other destinations (such as the lunar surface) could be investigated if such results were desired.

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National Aeronautics and Space Administration
Huntsville, Alabama, May 1978

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16. ABSTRACT

The possibility of space disposal of iodine waste from nuclear power reactors is investigated. The space transportation system utilized relies upon the Space Shuttle, a liquid hydrogen/liquid oxygen Orbit Transfer Vehicle (OTV), and a solid propellant final stage. The iodine is assumed to be in the form of either an iodide or an iodate, and calculations assume that the final destination is either solar orbit or solar system escape.

It is concluded that space disposal of iodine is feasible.

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